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FUEL-RICH PLUME COMBUSTION.(U)  
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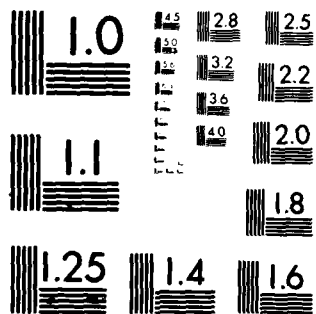
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NAVSEA Propulsion Research Program

Program Element 61153N

Fuel-Rich Plume Combustion\*

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## Background

Turbulent mixing and combustion of fuel-rich plumes in subsonic and supersonic airstreams are relevant to problems in gas generator ramjets (ducted rockets), slurry fueled ramjets, and external burning/base burning systems.

The ability to optimize the performance of these systems requires both the qualitative, experimental insight into the critical physical and chemical processes affecting the performance and the analytical modeling of the important aspects of the combustion flow fields.

Significant progress has recently been made under this program to qualitatively clarify the critical processes for achieving high combustion efficiencies in solid boron propellant gas generator ramjets and external burning propulsion systems. The purpose of the current effort is to obtain detailed, quantitative data that would specifically aid development and evaluation of analytical modeling of the complex flow field in gas generator ramjets. While in the previous work, the experimental methods have been qualitative (motion picture coverage, water flow tunnel) with limited use of intrusive probes and the hardware has been two-dimensional. The current program makes use of nonintrusive diagnostic methods in addition to intrusive probes and the hardware is axisymmetric.

Our previous work related to gas generator ramjets with solid boron propellants resulted in a new understanding of the fuel-rich, particle-laden plume ignition process in a subsonic airstream. Tests showed that as long as the gaseous fuel components from the gas generator can be made to react with the air in the ramjet combustor before excessive mixing occurs, the resulting gas-phase combustion temperatures will be high enough to initiate high boron reaction rate.<sup>1-3</sup> In these tests with coaxially and non-coaxially mixing fuel and airstream, two situations occurred in which the gas-phase combustion process produced insufficient temperatures. First, particularly at low secondary chamber pressure, the gaseous fuel components did not ignite in the fore-end of the mixing region where theoretical near-stoichiometric gas-phase combustion temperatures prevail. When gaseous fuel components ignited further downstream, the gas-phase combustion temperatures were too low because excess air mixing had already taken place. Second, although the tested mixing and flameholding device established a gas-phase flame at the beginning of the mixing region, the mixing was too rapid and the temperatures were again generally too low.

Our previous work related to external burning propulsion (base drag reduction) has shown that external burning in the supersonic airstream is only attractive with additional combustion in the subsonic near wake region.<sup>4-5</sup> This new concept of combined external burning/base burning was further evaluated under Air Force funding.<sup>6-9</sup> In this NAVSEA program, external burning was further investigated in combination with contoured aft-bodies instead of blunt bases used in the earlier studies.<sup>10</sup> Higher base pressures (compared to blunt bases) were achieved with external burning in conjunction with properly contoured aft bodies.

### Technical Objective

The objective of the current work is to obtain detailed experimental data in axisymmetric flow fields relevant to solid boron gas generator ramjets which would aid evaluation and guidance of analytical techniques.

### Approach

Experiments are being performed using an axisymmetric gas generator ramjet. Axial and radial profiles of pressure, velocity, turbulence intensity, temperature, and species concentration are being determined using non-interference optical diagnostic techniques (laser doppler velocimeter (LDV)) and intrusive probes. The experimental data are being compared with analytical models developed by Science Application, Inc. (SAI) under an Air Force Office of Scientific Research (AFOSR) contract.

An axisymmetric, 5-inch diameter laboratory ramjet combustor was built and checked out. Experiments were initiated using (1) an LDV and a hot-wire anemometer for velocity and turbulence intensity measurements, (2) coated thermocouples for temperature measurement, and (3) a gas chromatograph for analysis of gas samples.

A schematic diagram of the ramjet combustor is shown in Figure (1). For the fuel-rich plume mixing and combustion studies, the combustor consists of (1) a gaseous fuel gas generator with a hydrogen/oxygen torch igniter, (2) a powder feed system, and (3) a ramjet combustor in which the particle-laden fuel-rich reaction products coaxially mix with the air. Downstream of the air inlet, a perforated plate and a honeycomb grid are used to achieve a uniform air flow. Hot wire anemometer measurements were made to determine optimum design of the flow straightener arrangement to achieve axisymmetric air flow conditions (velocity and turbulence intensity). Downstream of the flow straightener, turbulence producing screens and swirlers are used.

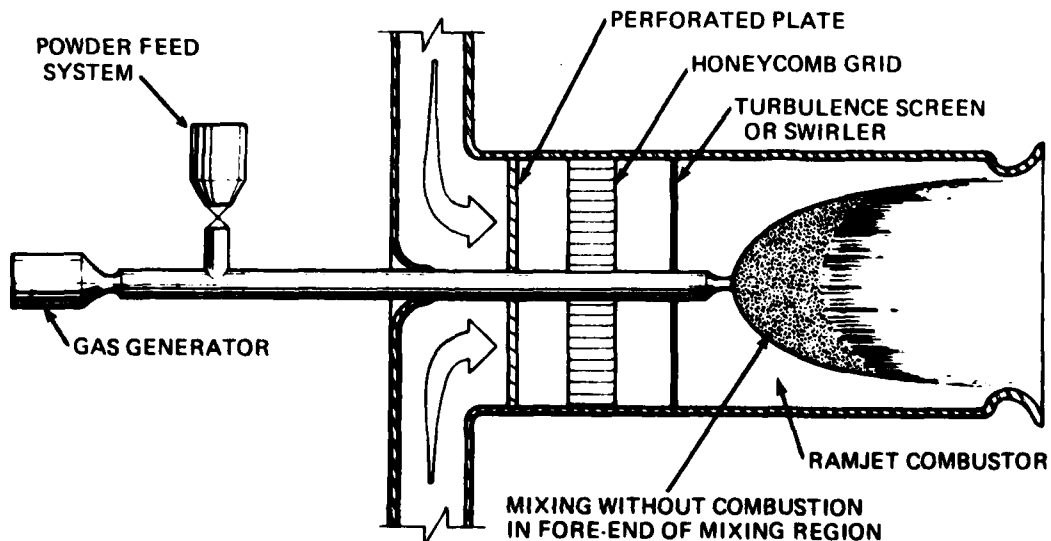


Figure 1. Fuel-Rich Plume Combustion in Axisymmetric Flow.

The combustor was checked out using ethylene, oxygen, and nitrogen in the gas generator to simulate solid propellant reaction products. Experimental methods consisted of pressure measurements to determine fuel and air mass flows and combustion pressures in the gas generator and ramjet combustor. Visible observation of the flame characteristics was made possible through a plexiglass tube section in the ramjet combustor. Proper functioning of the entire system was demonstrated.

Ignition and flame characteristics in the ramjet combustor were studied as function of varying operational conditions in the gas generator (temperature, exhaust velocity) and ramjet combustor (turbulence intensity of air flow, pressure, equivalence ratio). Based on these results, test conditions for the detailed flow measurements were selected.

Preparations were made to measure the air flow characteristics with an LDV. Data linkage between the two-color, three-beam LDV and the PDP 11/03 computer was established. Presently, the LDV is capable of measuring two perpendicular velocity components at 3000 samples per position. One sample corresponds to one mean velocity to be calculated as well as the standard deviation for turbulence analysis. Also, skewness and kurtosis are derived and graphically displaced for comparison to the normal distribution. Figure (2) shows a velocity histogram of one velocity component for velocity measurements at one position in an airstream with atomized water. In the figure, the percentage of the total data points (3000 samples) is shown on the ordinate, the deviation of the velocity of the individual particles,  $V(I)$ , from the mean velocity,  $V_{MEAN}$ , on the abscissa. It may be seen that for only about 2.4% of the total particles  $V(I)$  was equal to  $V_{MEAN}$  in this highly turbulent flow with a computed turbulence intensity of 15.7%.

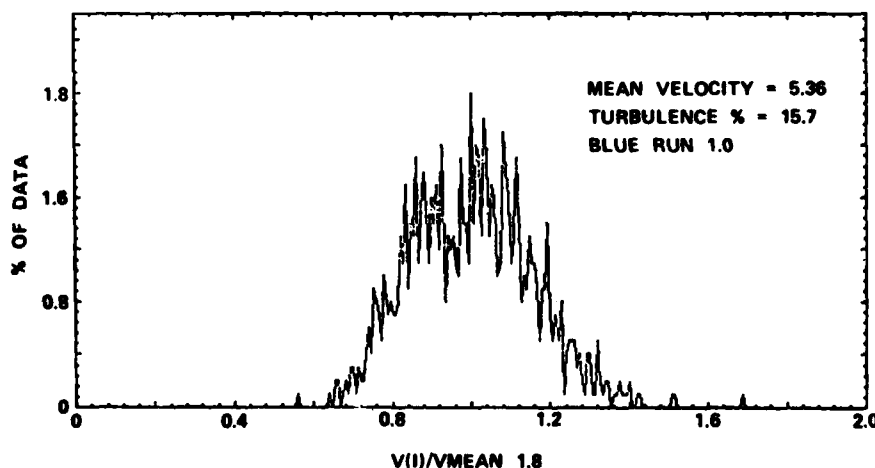


Figure 2. Velocity Histogram.

Experiments were started to determine combustion temperature profiles with tungsten/rhenium thermocouples. One example is shown in Figure 3. To increase the oxidation resistance and reduce the catalytic reactions, the beads of these thermocouples were coated with beryllium and yttrium oxide. Temperature measurements in a propane torch flame at about 2500°F showed that the temperatures measured with the coated thermocouples were about 6% lower than those measured with the uncoated thermocouples, probably because of reduced catalytic reactions. It was also noted that the coated thermocouples melted at a higher temperature than the uncoated thermocouples, probably because of increased oxidation resistance.

Experiments were started to determine gaseous species concentration profiles with isokinetic, water-cooled probes. The sample gases are being analyzed with a gas chromatograph.

Three papers were prepared for presentation of test results achieved in FY 1980.

The first paper, Ref. 11, describes experiments with external burning along specially contoured afterbodies (EB/BC) for base drag reduction. With EB/BC, fuel-rich solid propellant reaction products are injected in thrusting (axial) direction. The effective base pressure rise of EB/BC was higher than previously achieved with external burning/base burning (EB/BB).

The second paper (Ref. 12) describes the use of the windowed combustor and the water tunnel to provide qualitative insight into the critical processes for achieving high combustion efficiency in gas generator ramjets using solid non-metallized propellants.

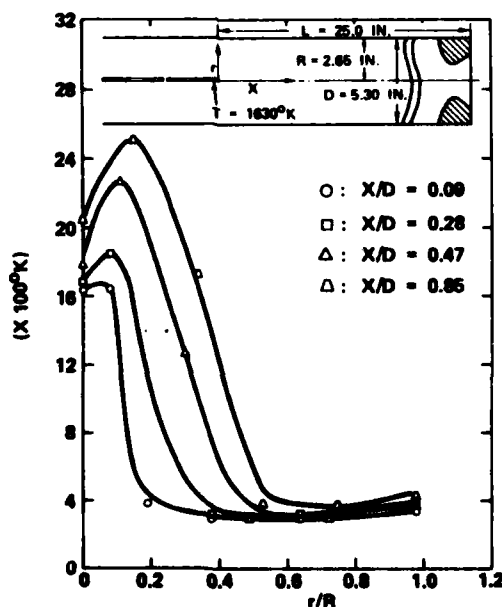


Figure 3. Temperature Distribution in the Gas Generator Ramjet Combustor.

## Plans (FY 1982)

1. Detailed flow measurement in axisymmetric flow fields of gas generator ramjets without dump will be concluded. Parameters, which will be varied, include gas generator exhaust velocity, turbulence intensity of air flow, swirl number of air flow, ramjet combustor pressure, and boron particle loading. Close interaction between NAVWPNCEN and SAI will continue to interpret experimental results and check/improve models.
2. Detailed flow data will be obtained for fuel-rich plume ignition and combustion for axisymmetric flows with dump. Tests will be made with and without boron particles. In specific, the interrelationship between (1) the aerodynamics and air-to-fuel ratio distribution of the approach flow to the dump region, (2) reaction in the recirculation zone, and (3) ignition and combustion of the core region will be studied. Tests will be performed at overall combustion conditions at which plume ignition was not achieved without dump. In the presence of a dump, plume ignition can be expected because fuel-rich products will be entrained into the recirculation zone, where auto-ignition may occur or ignition may be initiated by an external source. The hot products from the recirculation zone will then ignite the fresh mixture of air and fuel of the approach flow.

For the intercoupled mechanisms of the plume ignition process with dump, the aerodynamics and the air-to-fuel ratio distribution at the dump region will be decisive because they determine the relative degree of air and fuel mixing into the recirculation zone and therefore the recirculation zone combustion temperature. This temperature in turn will be critical for the core-region ignition process.

Detailed measurements will be made in the approach flow (velocity, temperature, species concentration, and turbulence level), recirculation zone (temperature and species concentration). Intrusive probes and the LDV will be used as described for the FY 1981 studies. Two of the major variables in the plume ignition tests with dump will be the axial position of the gas generator nozzle (to vary air-to-fuel ratio in the approach flow at the dump region) and the step height at the dump region to vary volume/length of the recirculation zone.

Close interaction between NAVWPNCEN and SAI will continue to interpret experimental results and check/improve modeling.

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